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An Experimental and Theoretical Study of the Aerodynamic Characteristics of Some Generic Missile Concepts at Mach Numbers From 2 to 6.8

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AN EXPERIMENTAL AND THEORETICAL STUDY OF THE AERODYNAMIC CHARACTERISTICS OF SOME GENERIC MISSILE CONCEPTS AT MACH NUMBERS FROM 2 TO 6.8

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Summary

A study has been made of the experimental and theoretical aerodynamic characteristics for some generic high-speed missile concepts at Mach numbers from 2 to 6.8. The basic body for this study had a length-to-diameter ratio of 10 with the forward half being a modified blunted ogive and the rear half being a cylinder. Modifications made to the basic body included the addition of an afterbody flare, the addition of highly swept cruciform wings and the addition of highly swept aft tails. The effects of some controls were also investigated with all-moving wing controls on the flared body and trailing-edge flap controls on the winged body.

The results indicated that the addition of a flare, wings or tails to the basic body all provided static longitudinal stability with varying amounts of increased axial force. The control arrangements were effective in producing increments of normal-force and pitching-moment at the lower Mach numbers. At the highest Mach number, the flap control on the winged body was ineffective in producing normal-force or pitching-moment but the all-moving wing control on the flared body, while losing pitch effectiveness, still provided normal-force increments.

Calculated results obtained through the use of hypersonic impact theory were in generally good agreement with experiment at the higher Mach numbers but were not accurate at the lower Mach numbers.

Introduction

Current tactical missiles achieve speeds ranging from subsonic to about a Mach number of 4. Missile flight at higher supersonic speeds is desirable from the standpoint of reducing the time of flight from launch to target. Reducing the time-to-target should increase the probability of successful contact especially against evasive targets and should also reduce the detection time available to defensive systems.

Some studies have been made in the past that have application to the aerodynamic design of high speed missiles (refs.1-7 for example). The attainment of the goals of speed and accuracy would require the use of suitable materials and structure; good stowage, launch and propulsion characteristics; good guidance systems and good aerodynamic stability and control behavior.

The purpose of this paper is to examine the aerodynamic characteristics of some missile concepts at Mach numbers from 2.0 to 6.8 and to determine the extent to which some calculative techniques can be used to predict these characteristics. Experimental data are extracted from references 2 to 5. Calculations are made using the Hypersonic Arbitrary-Body Program (ref.8).

Symbols

The results are referred to the body axes system. The moment reference point is at the 50-percent body length station.

A cross-sectional area of cylindrical portion of body

C_A axial-force coefficient, axial-force/qA

C_m pitching-moment coefficient, pitching-moment/qAl

C_{m_α} static longitudinal stability parameter measured near zero angle of attack

C_{m_δ} pitching-moment due to control deflection

C_N normal-force coefficient, normal-force/qA

C_{N_α} normal-force curve slope measured near zero angle of attack

C_{N_δ} normal-force due to control deflection

l body length

M Mach number

q dynamic pressure

r body radius

x body station

α angle of attack, degrees

δ control deflection, positive trailing-edge down, degrees

Models and Tests

The basic body for this study is shown in Figure 1 together with the modifications intended to provide stability and to augment the normal force. The basic body consisted of a 5-caliber forebody with a rounded nose followed by a conical section that faired into a 5-caliber afterbody. The modifications consisted of the addition of a 2-caliber 10-degree flared afterbody, the addition of 85 degree delta cruciform wings and the addition of 75 degree delta cruciform tails. The study was extended to include the effects of controls for two of the concepts as shown in Figure 2. The winged configuration was revised to include trailing-edge flap controls. The flared configuration was revised to include 70 degree cruciform delta all-movable forward wing controls. Geometric characteristics for the models are listed in Tables I to III. Further details of the models are presented in references 1-5. Tests were made in several NASA-Langley wind tunnels. Results for the basic body and the modified bodies were obtained in the Unitary Plan wind tunnel (UPWT) for M=2.29 to 4.65. Results for the configurations with controls were obtained in the 4-by 4-foot supersonic pressure tunnel (4'SPT) for M=2.01, the UPWT for M=4.65 and the 11-inch hypersonic tunnel (11"HT) for M=6.8. The axial force was corrected to free-stream static pressure at the base. Further test details may be found in references 1-4.

Discussion

Longitudinal Characteristics for the Basic Body and Modifications

The longitudinal characteristics as a function of angle of attack are presented in Figure 3 for the basic body and the basic body with various modifications at Mach numbers of 2.3 and 4.65. The basic body does, of course, have the least axial force but is also the least effective in producing normal force and also is the least stable. The modifications to the basic body were intended to provide greater normal force and to provide positive static longitudinal stability. Each modification resulted in increased axial force with the greatest increase resulting from the addition of the flare. Each of the modifications were effective in increasing the normal force with the wing being the most efficient. Each of the modifications provided positive static longitudinal stability. There is a pronounced nonlinear increase in normal force with increasing angle of attack that most likely results from the progressive development of vortex lift. Some nonlinearity is also apparent in the variation of pitching moment with angle of attack.

The variation of some longitudinal parameters near zero angle of attack for Mach numbers from 2.3 to 4.65 is shown in Figure 4. The increments in axial force due to the modifications are as might be expected and are consistent over the Mach number range. The greatest increase in normal-force slope results from the addition of the wing and is due, in part, to the normal force of the wing panel itself and, in part, to the mutual carry-over of normal force between the wing and body surfaces. The increase in normal-force slope resulting from the tails and from the flare are very nearly the same. The normal-force slope near zero angle of attack for each of the configurations is essentially constant over the Mach number range. Each of the modifications resulted in longitudinally stable configurations. The stabilizing increment provided by the addition of the flare to the body was nearly constant over the Mach number range and the result was an increase in stability with increasing Mach number. Both the wing and the tail additions provided substantial longitudinal stability - the wing being somewhat more effective because of the larger area for the wing and the increased amount of lift carried over to the afterbody. However, the stability provided by the wing or the tail decreases with increasing Mach number because of a decrease in lift-curve slope for these panels with increasing Mach number. As a result, at M=4.65, there is little difference in the stability level provided by the wing, tail or flare with the indication being that, with increasing Mach number,the stability level may continue to increase with the flared concept and decrease with the wing and tail concepts.

Longitudinal Control Characteristics

Some effects of pitch control deflection are shown in Figure 5 for the wing with trailing-edge flaps at Mach numbers of 4.65 and 6.8. The flaps were effective in producing negative increments in normal force with resulting positive increments of pitching moment. The flap control was considerably less effective at M=6.8 than at M=4.65, however.

Some effects of pitch control deflection are shown in Figure 6 for the flared-body with all-moving wings. The all-moving wing was quite effective in producing positive normal force and positive pitching moments at M=4.65. At M=6.8, the all-moving wing indicated increased effectiveness in producing normal force but the pitching moment effectivness was substantially reduced.

Some pitch control characteristics for the flap and the all-moving wing configurations are shown in Figure 7 as functions of Mach number. These results indicate a higher value of axial force over the Mach number range for the flared configuration as might be expected. However, the stability level progressively increases with increasing Mach number for the flared configuration while that for the winged configuration decreases. The effectiveness of the trailing-edge flap in producing pitching-moment and normal force is good at M=2 but the effectiveness progressively decreases with Mach number and, at M=6.8, the flap is essentially ineffective. The all-moving wing is effective in producing pitching-moment and normal force at M=2. The pitch effectivness progressively decreases with Mach number but the normal force effectiveness is retained over the Mach number range. Thus, while the wing control does not produce angular rotation, it does provide for flight path changes through translation resulting from the normal force increments.

Calculated Results

Calculated results were made by the use of the Hypersonic Arbitrary-Body Aerodynamic Computer Program (ref.8). Computer-generated drawings of the test configurations are shown in Figure 8. Over the impact regions, the tangent-wedge method was used for the fins and the tangent-cone method was used for the bodies. For the shadow regions, the Prandtl-Meyer expansion from free-stream was used. Skin friction was determined by the method of Spaulding and Chi. Over blunt regions such as the nose and the wing leading edge, the modified Newtonian method was used.

Comparisons of the calculated results with experiment for the basic body and the body with modifications for M=2.3 and 4.65 are presented in Figures 9 to 12. At M=2.3, the calculations generally over-predict the axial force, the normal-force slope and the stability level but do depict the proper trends that result from the modifications. At M=4.65, however, the calculated results are in much better agreement with the experiment.

Comparisons of the calculated results with experiment for the configurations equipped with controls are presented in Figures 13 and 14 for the undeflected control case at M=2, 4.65 and 6.8. The characteristics for these configurations are over-predicted at M=2. At M=4.65 and 6.8 the calculated results for the normal force and the pitching moment are in generally good agreement with the experiment. The drag, however, is over-predicted, possibly because of the inability to simulate flow-field interference effects for these configurations.

Some calculations were made with controls deflected for the all-moving wing control. No attempt was made to calculate the trailing-edge flap case since the hypersonic arbitrary body program would not account for the interference flow fields from the wing to the flap. Results at M=4.65 and 6.8 for the all-moving wing deflected 10 degrees and 20 degrees are presented in Figures 15 and 16, respectively. These results indicate generally good agreement between experiment and theoretical calculations. Thus it appears that the calculative techniques used herein, while over-predicting the characteristics at M=2 and 2.3, were generally good in predicting the characteristics at M=4.65 and 6.8 and should be useful tools in the design process for high-speed missiles.

Concluding Remarks

The purpose of this paper has been to present some experimental and theoretical results that might be useful in the design of high speed missiles. Results are presented for a generic family of missiles over a Mach number range from 2.0 to 6.8. The configurations consisted of a basic body alone and with modifications that include an afterbody flare, a wing and a tail. In addition, some results were obtained for the winged cofiguration with trailing-edge flap controls and for the flared configuration with all-moving wing controls.
Some concluding observations are:

- The addition of the flare, the wings and the tails to the basic body all resulted in favorable increases in normal force and stability but at the expense of an increase in axial force.

- O The trailing-edge flap and the all-moving wing were both effective in producing pitch control at the lower Mach numbers but the effectiveness decreased to zero at the highest Mach number.
- O Both controls were effective in producing normal force at the lower Mach numbers but the effectivness for the flap reduced to zero at the highest Mach number while that for the all-moving wing was maintained.
- O Calculated results using hypersonic impact theory were in generally good agreement with experimental results at the higher Mach numbers but were not accurate at the lower supersonic speeds.

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8. Gentry,A.E.; and Smyth,D.N.: Hypersonic Arbitrary-Body Aerodynamic Computer Program (Mark III Version), Rep.DAC61552 (Air Force Contract Numbers F3361567C1008 and F3361567C1602), Douglas Aircraft Co., April 1968, Volume I-User's Manual, Available from DAC as AD851811, Volume II-Program Formulation and Listings, Available DAC as AD815812.

TABLE I. - GEOMETRY FOR BASIC BODY AND MODIFICATIONS

	BASIC-BODY	BODY-FLARE	BODY-WING	BODY-TAIL
BODY:				
Length, in	30.00	30.00	30.00	30.00
Diameter, in.	3.00	3.00	3.00	3.00
Cross-sectional area, sq. in. ..	7.07	7.07	7.07	7.07
Fineness ratio of nose	5.00	5.00	5.00	5.00
Length-diameter ratio	10.00	10.00	10.00	10.00
Moment-center location, percent length	50.00	50.00	50.00	50.00
FLARE:				
Length, in.		6.01		
Base diameter, in.		5.13		
Base area, sq. in.		20.66		
Leading-edge angle, deg.		10.00		
FINS:				
Area exposed, 2 fins, sq. in ..			34.36	9.55
Root chord, in.			19.12	5.97
Tip chord, in.			0	0
Span exposed, in.			3.20	3.20
Span total, in.			6.20	6.20
Taper ratio			0	0
Aspect ratio, exposed			0.268	1.07
Span diameter ratio			2.07	2.07
Leading-edge angle, deg.			85.00	75.00
Thickness, in.			0.1875	0.1875

TABLE II. - COORDINATES OF FOREBODY

x/l	r/l
0	0
.0088	.0099
.200	.0321
.233	.0358
.267	.0392
.300	.0421
.333	.0445
.367	.0465
.400	.0480
.433	.0491
.466	.0497
.500	.0500

TABLE III - GEOMETRY FOR CONFIGURATIONS WITH CONTROL SURFACES

	11" HT	4' SPT AND UPWT
Body:		
Length, in.	12.00	30.00
Diameter, in.	1.20	3.00
Cross-sectional area, sq. ft.	0.0078	0.0491
Length-diameter ratio of nose	5.0	5.0
Length-diameter ratio, total	10.0	10.0
Moment center location, percent length	50.0	50.0
Flare:		
Length, in.	2.40	6.0
Base diameter, in.	2.046	5.115
Base area, sq. ft.	0.0228	0.143
Apex, angle, deg.	10.0	10.0
Wings, including flaps:		
Area, exposed, of two panels, sq. in.	4.77	28.96
Root chord, exposed, in.	7.64	19.12
Tip chord, in.	0	0
Span, exposed, in.	0.54	1.34
Aspect ratio, exposed	0.25	0.25
Leading-edge sweep angle, deg.	85.0	85.0
Span-diameter ratio, total	1.89	1.89
Thickness, in.	0.075	0.1875
Trailing-edge flaps:		
Area, per pair, sq. in	1.30	8.04
Span, each, in.	0.54	1.34
Chord, each, in.	1.20	3.00
Percent of fin area	27.2	27.2
Leading-edge sweep, deg	0	0
Hinge line, percent body length	93.3	93.3
Hinge line, percent chord	33.3	33.3
Gap, in.	0.04	0.1
All-movable controls:		
Area, exposed, per pair, sq. in.	2.50	15.70
Root chord, in.	2.55	6.40
Tip chord, in.	0.14	0.32
Span, exposed, in.	0.89	2.225
Leading-edge sweep angle, deg.	70.0	70.0
Hinge line, percent body length	46.7	46.7
Hinge line, percent root chord	68.7	68.7
Thickness, in.	0.075	0.1875

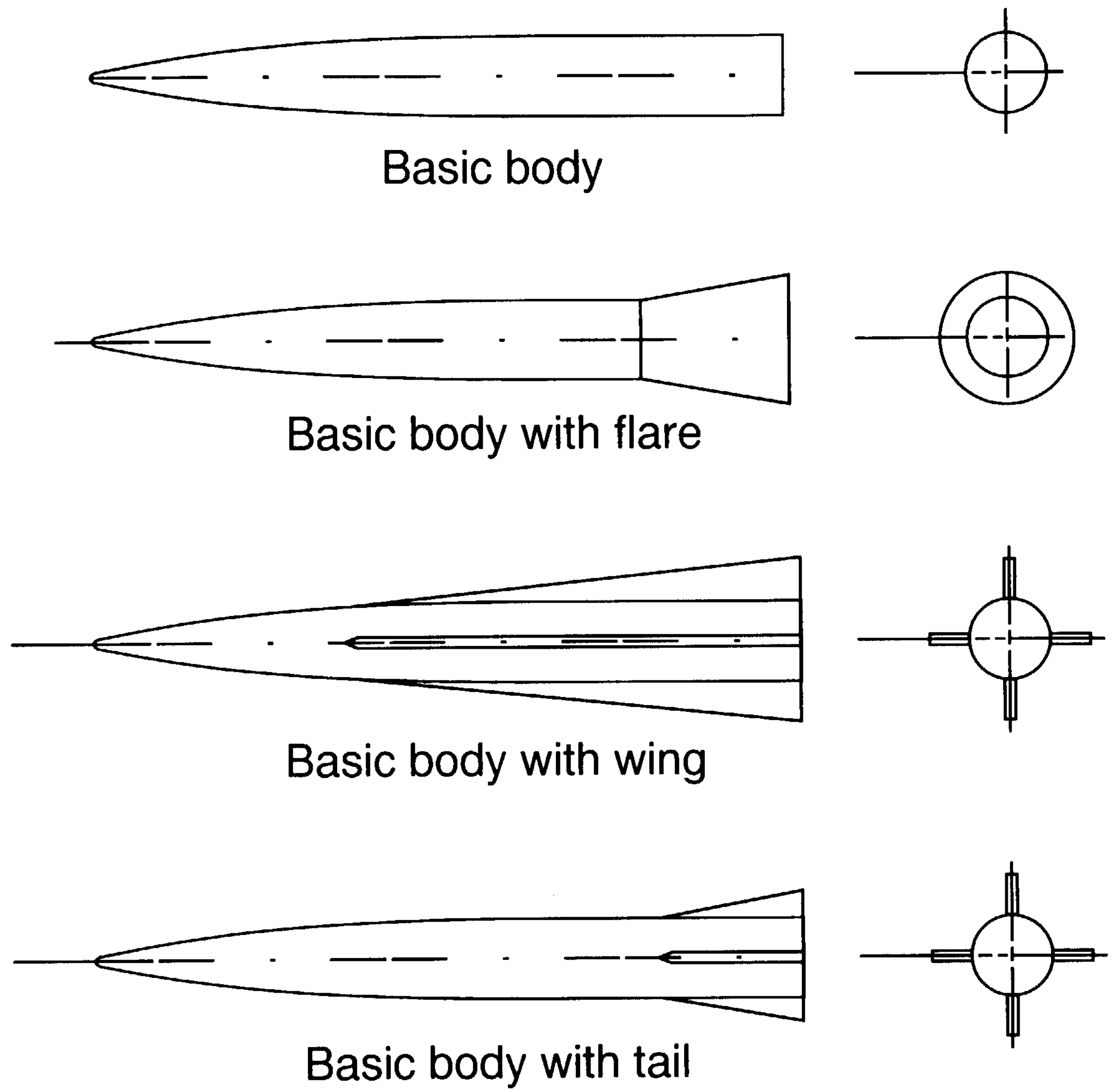

Figure 1 - Basic body and modifications

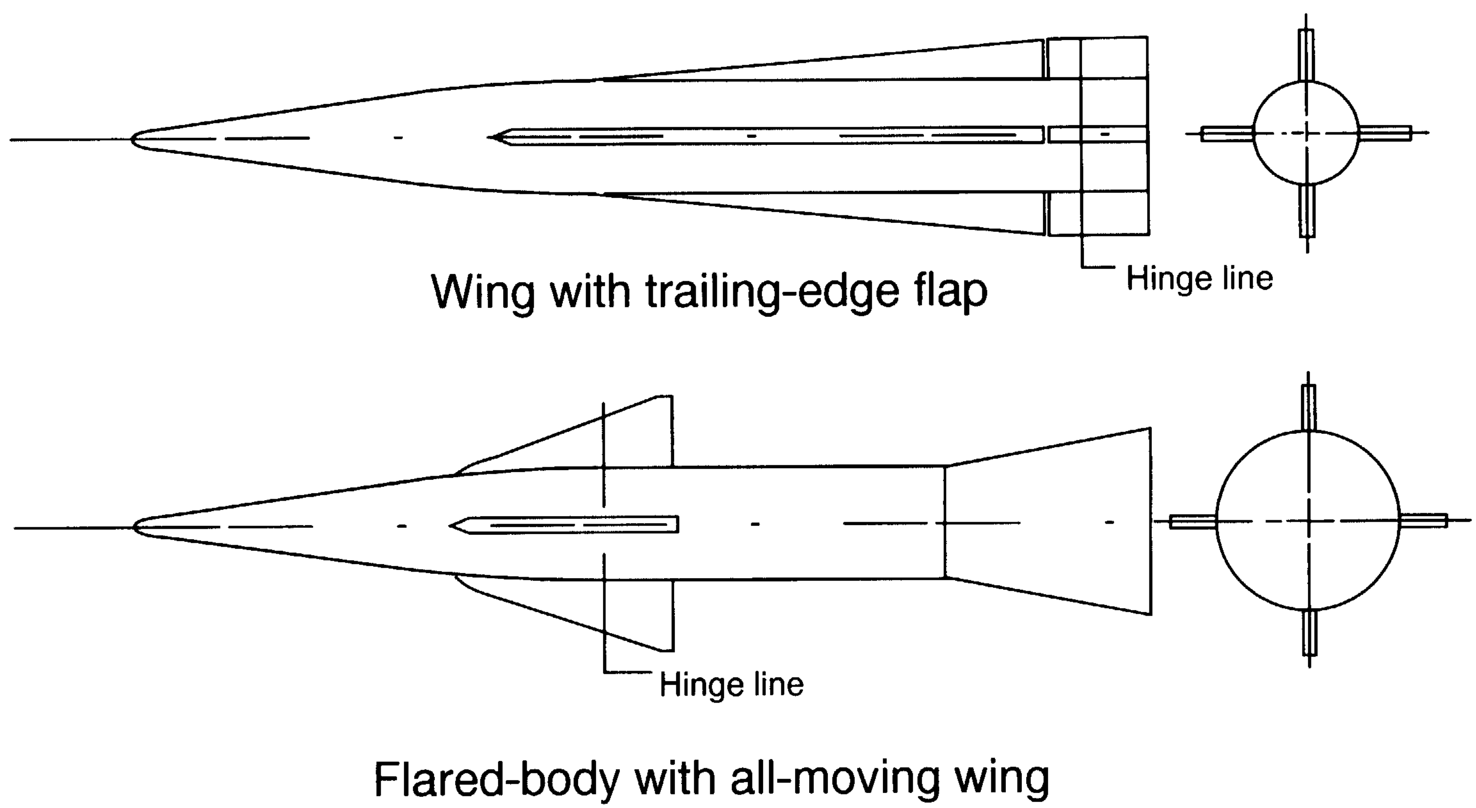

Figure 2 - Configurations with control surfaces.

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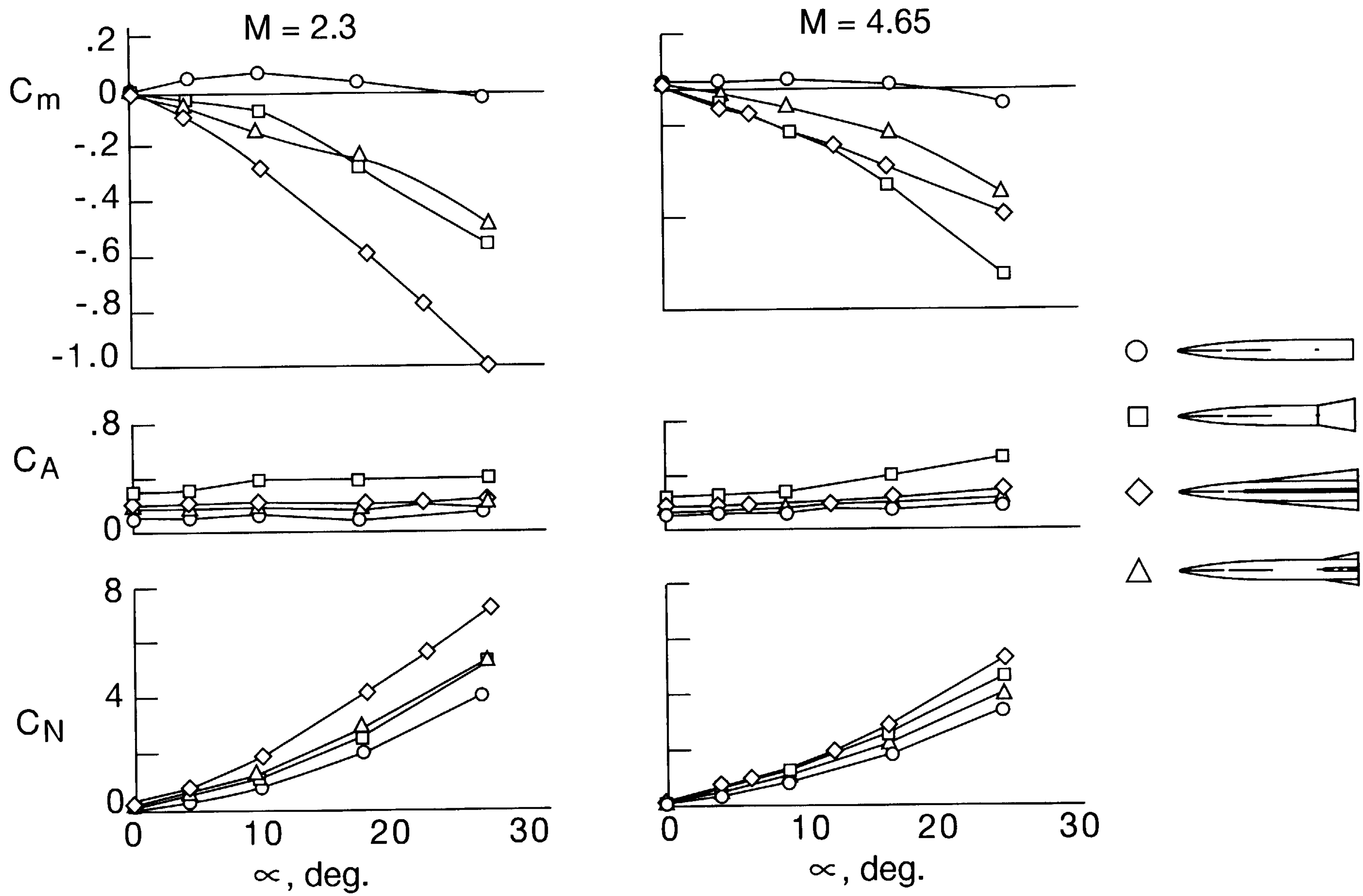

Figure 3 - Longitudinal characteristics for basic body and modifications

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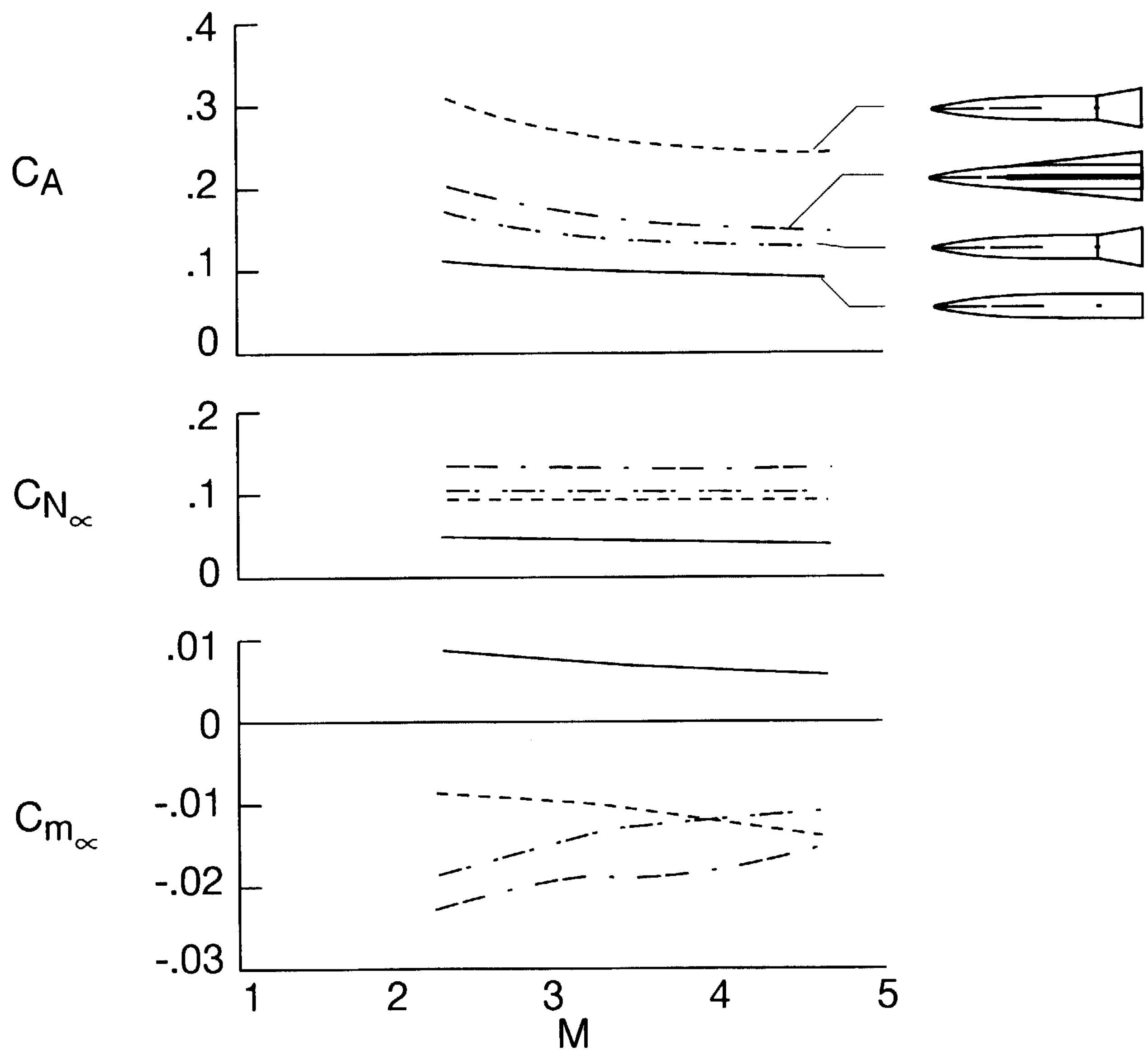

Figure 4 - Variation of some longitudinal parameters with Mach number for the basic body and modifications, $\alpha = 0°$.

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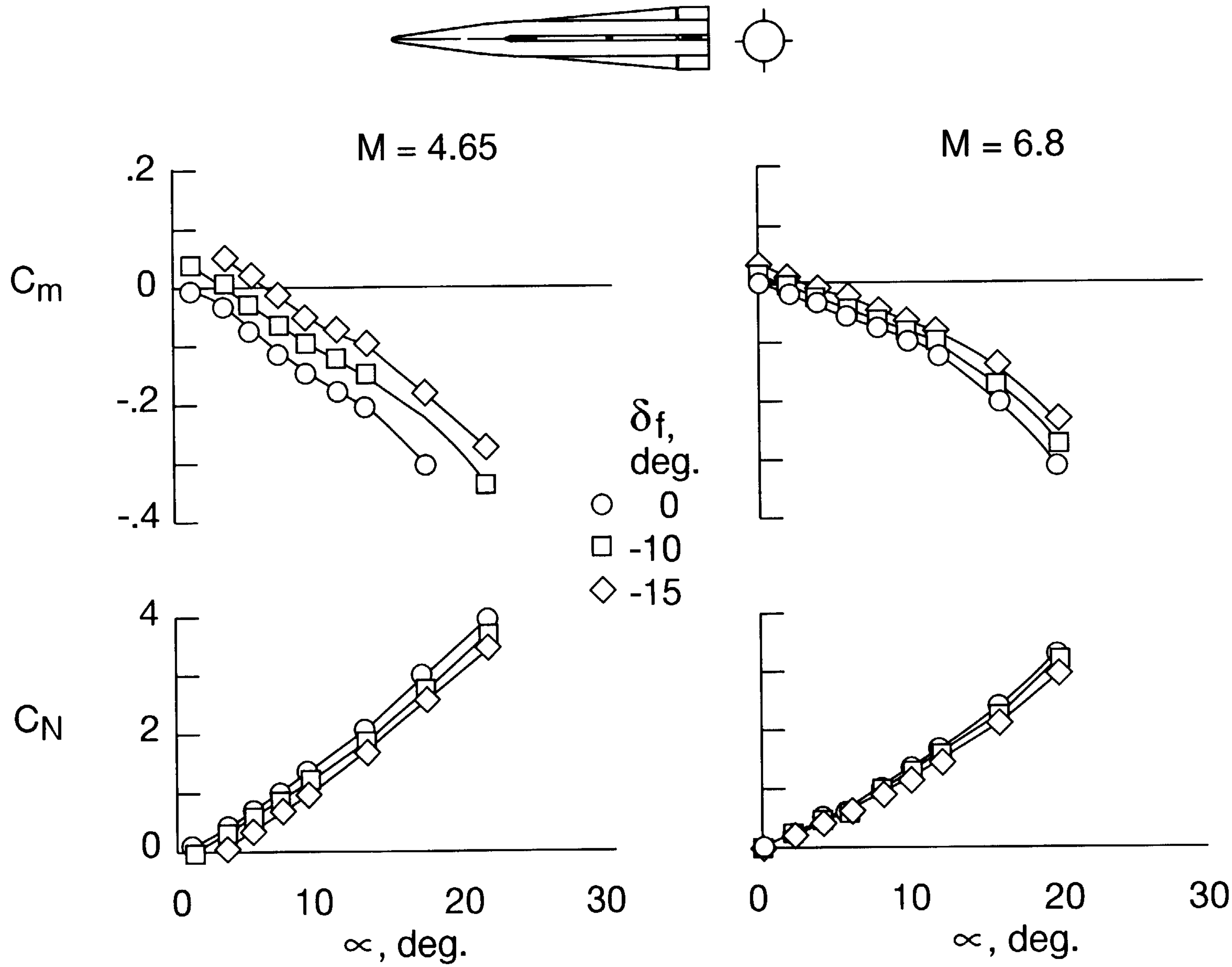

Figure 5 - Control characteristics for winged configuration with trailing-edge flaps.

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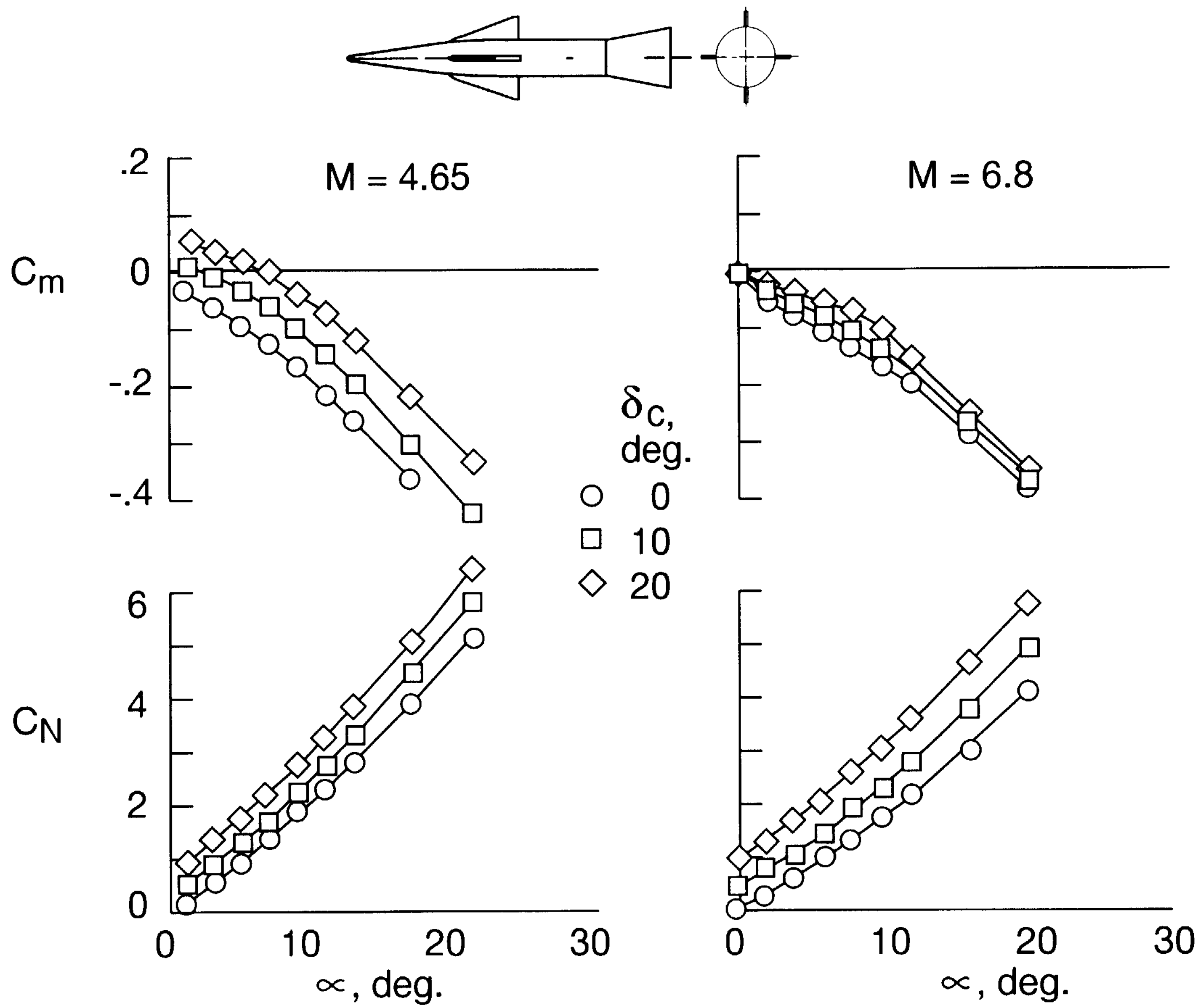

Figure 6 - Control characteristics for flared configuration with all-moving wing.

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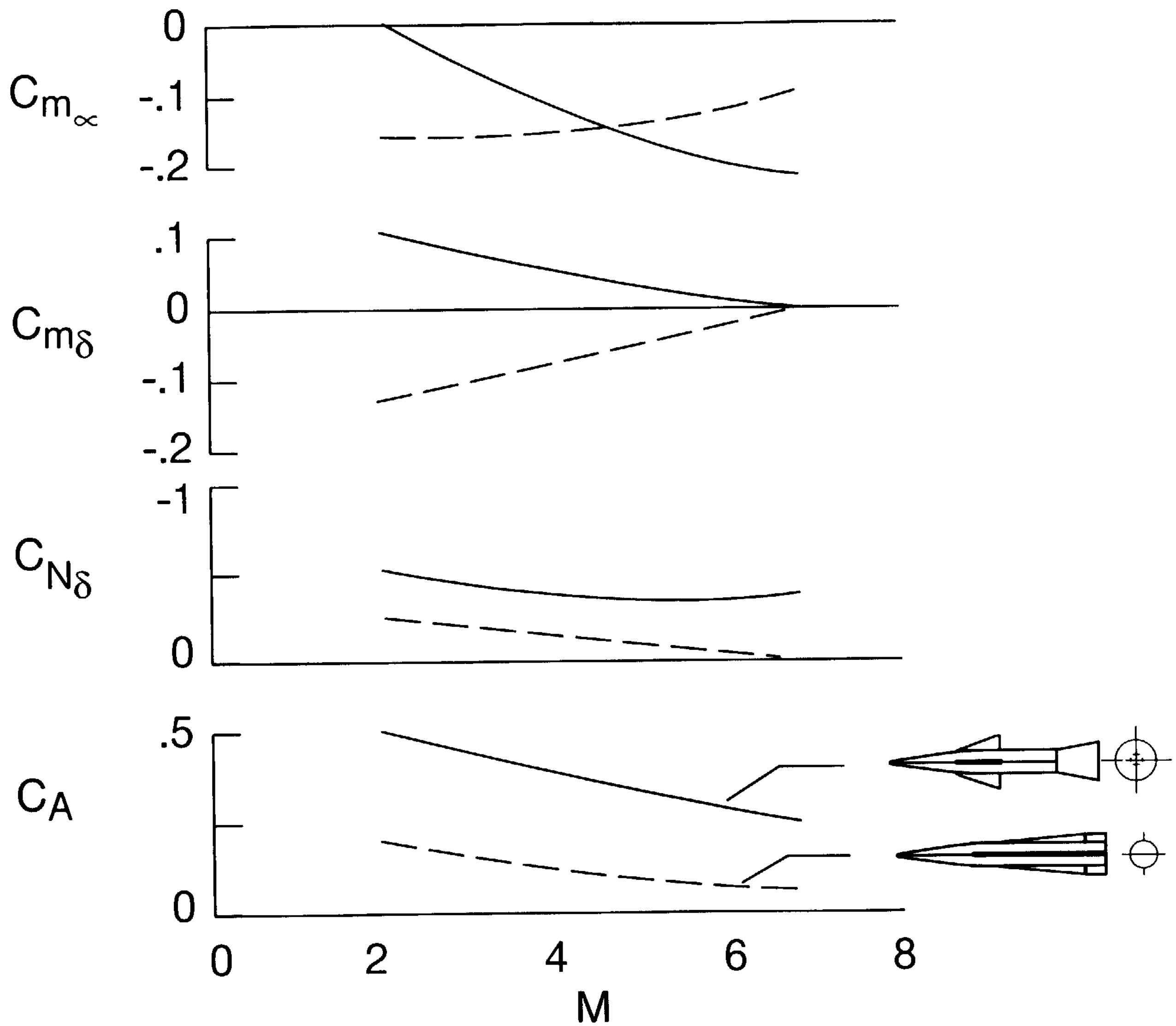

Figure 7 - Variation of some longitudinal parameters with Mach number for winged and flared configurations, $\propto = 0°$.

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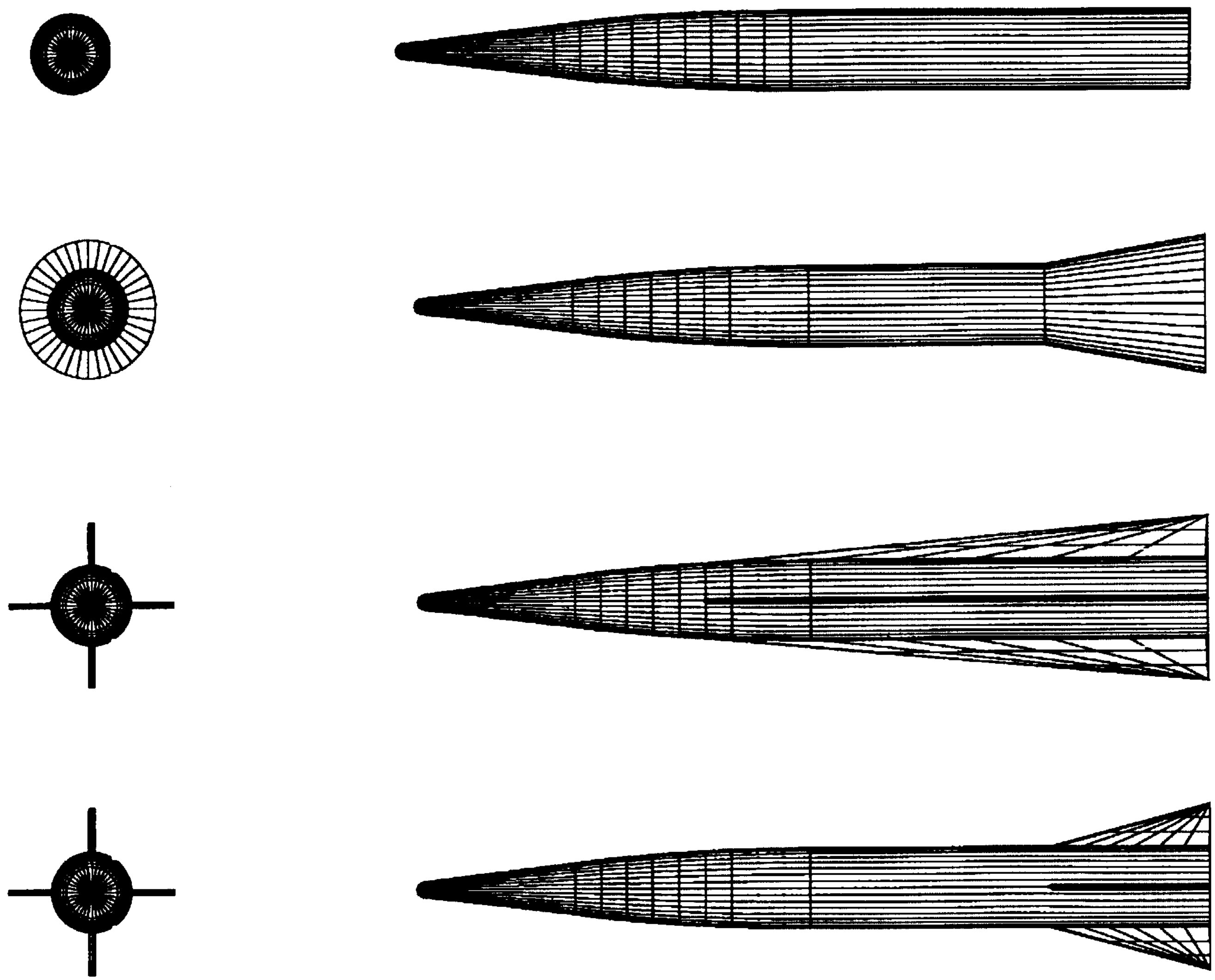

(a) - Basic body and modifications.

Figure 8 - Computer-generated drawings.

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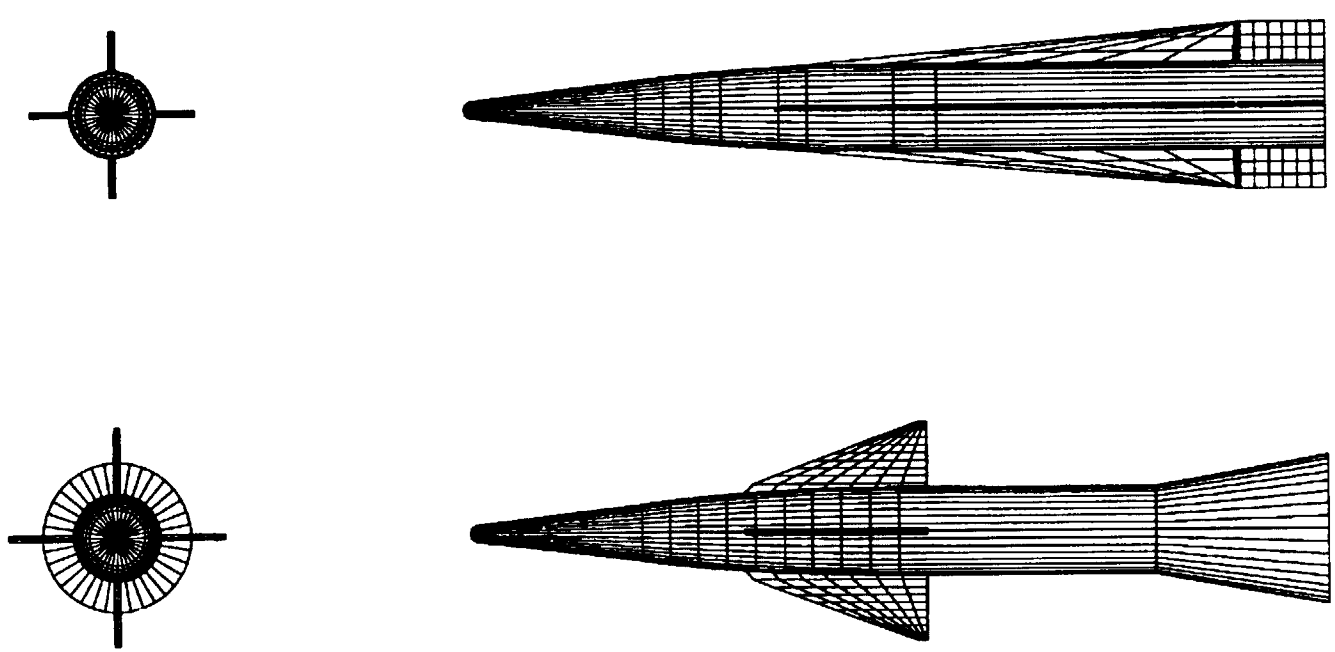

(b) - Configurations with controls.

Figure 8 - Concluded.

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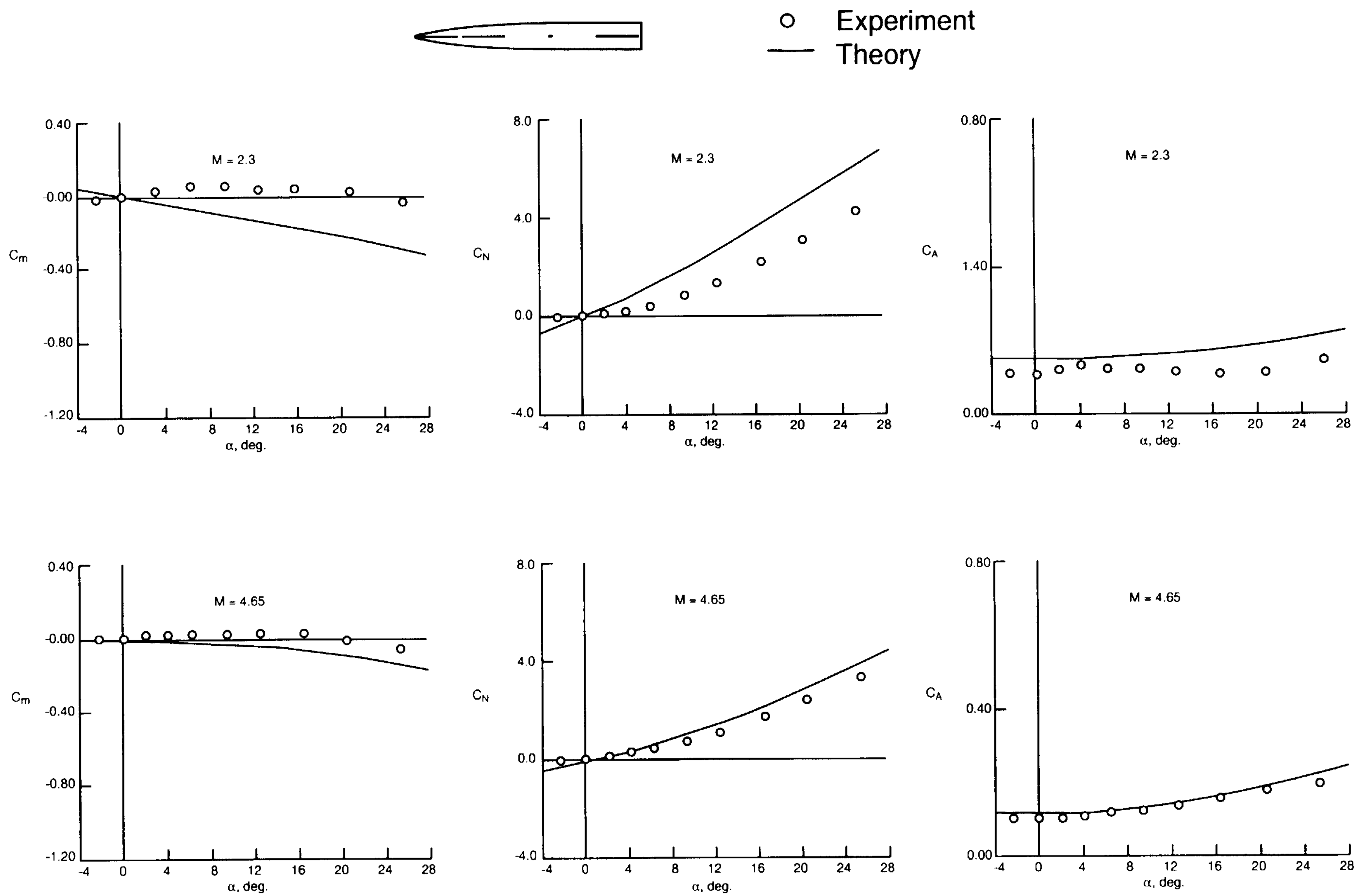

Figure 9 - Comparison of experiment and theory, basic body.

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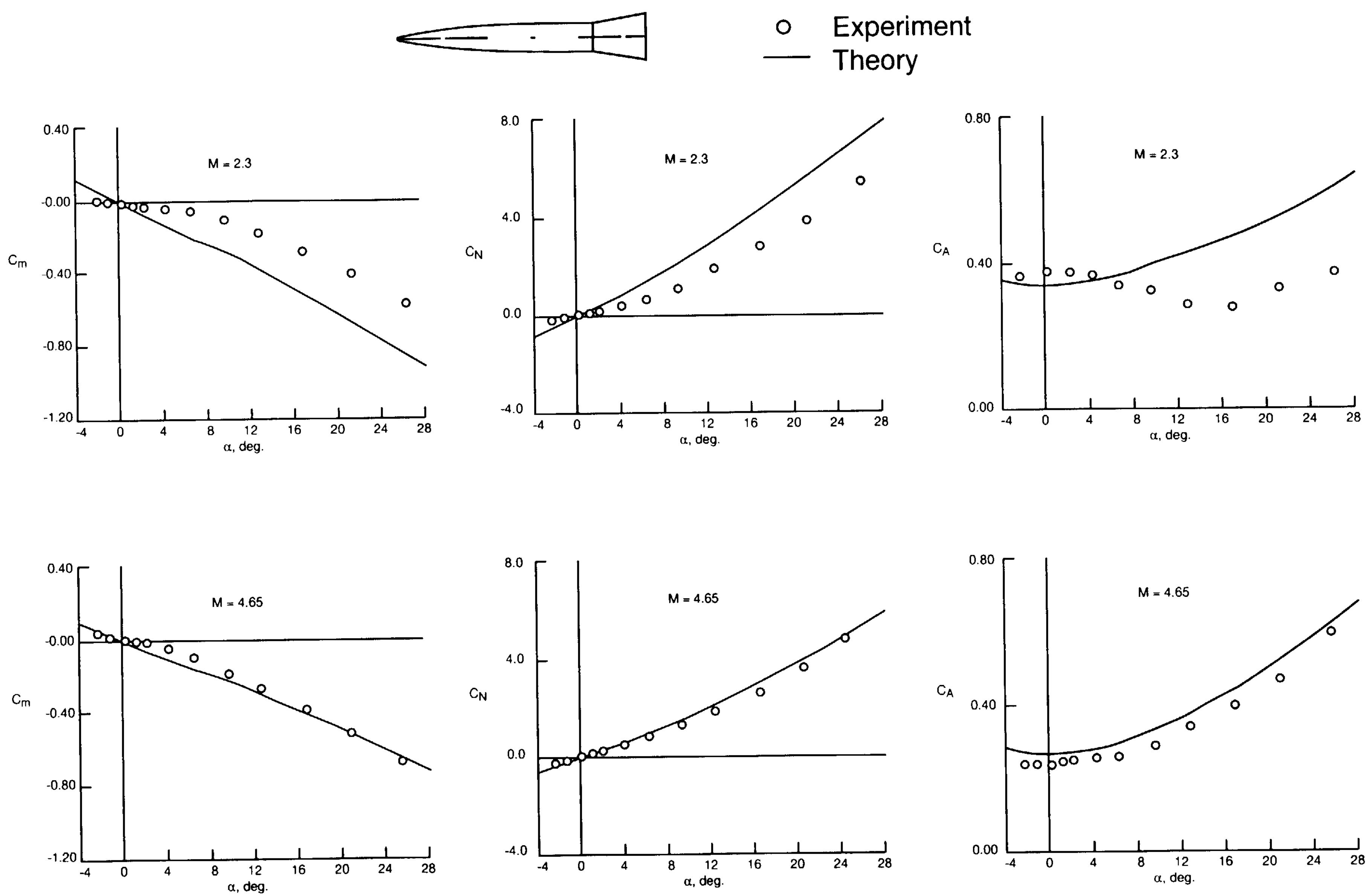

Figure 10 - Comparison of experiment and theory, body-flare.

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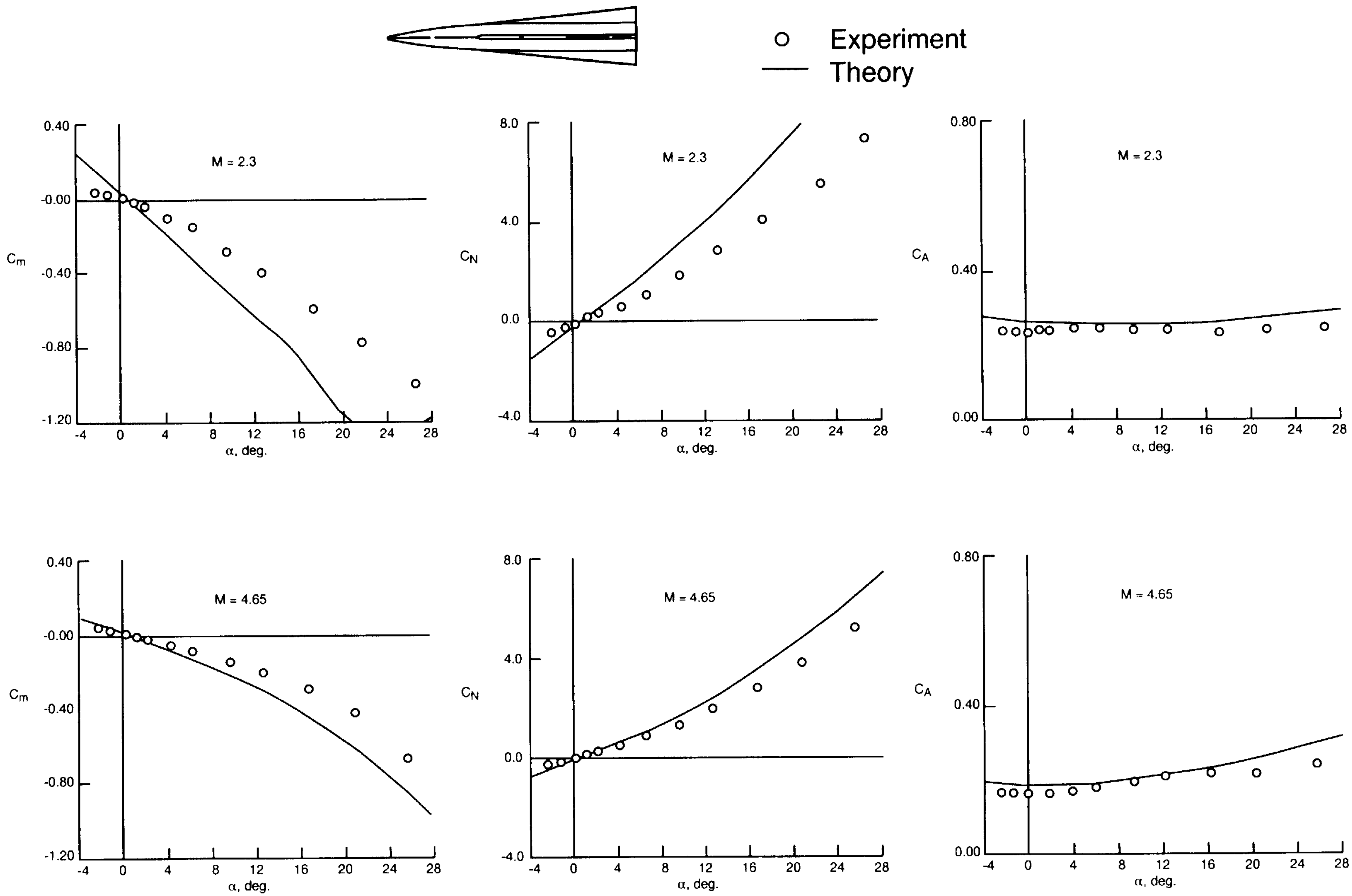

Figure 11 - Comparison of experiment and theory, body-wing.

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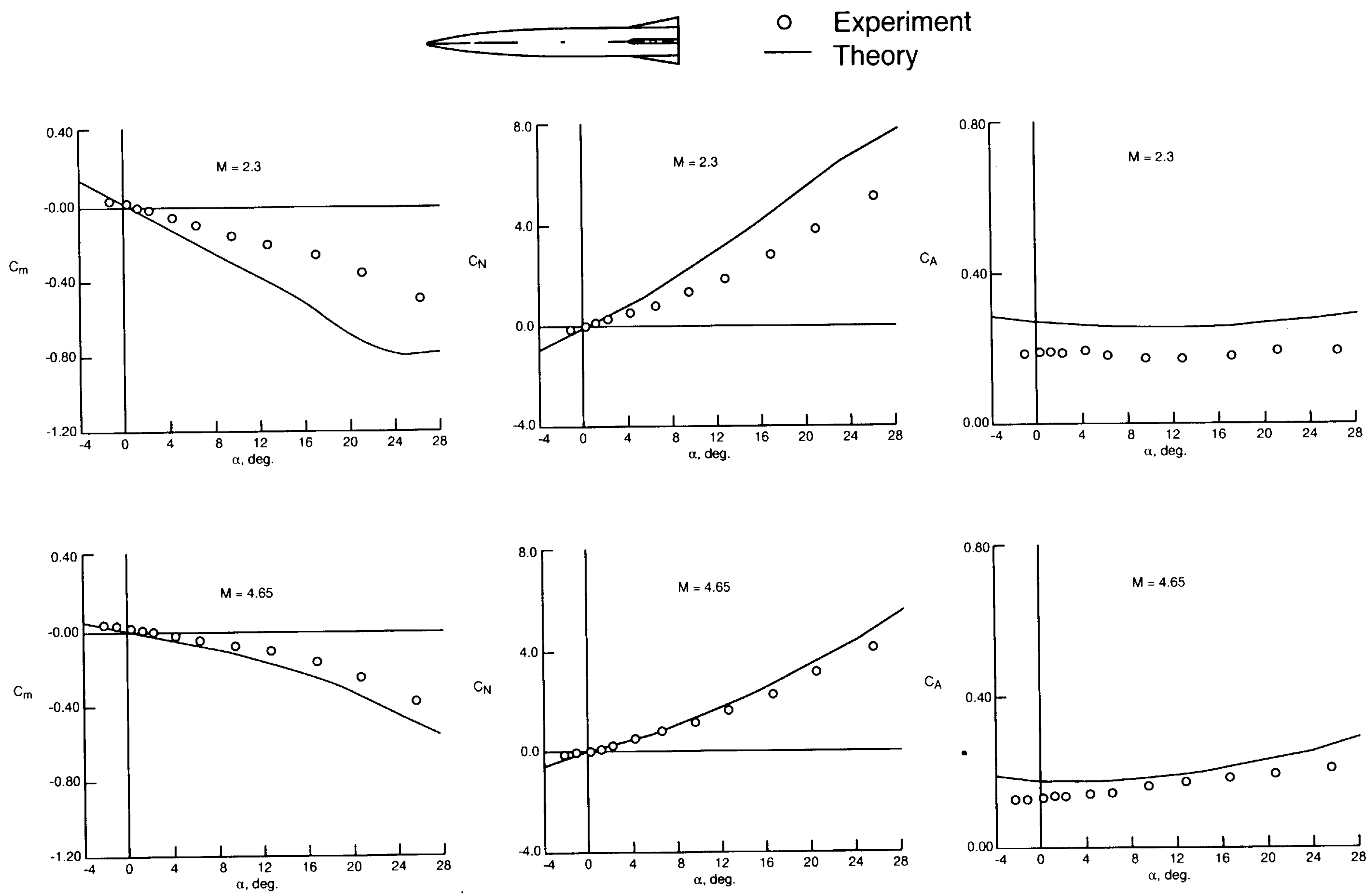

Figure 12 - Comparison of experiment and theory, body-tail.

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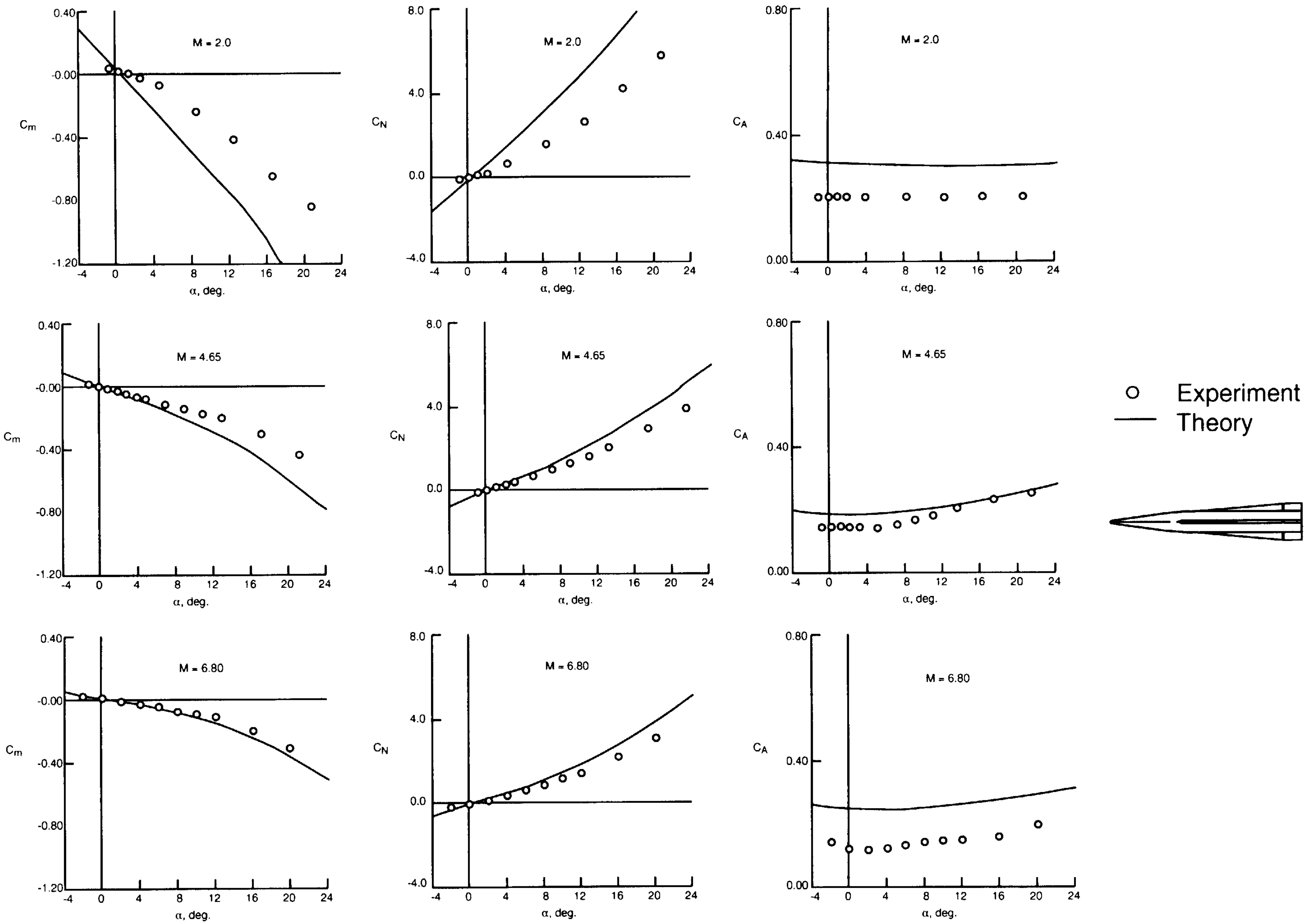

Figure 13 - Comparison of experiment and theory, winged-configuration with trailing-edge flaps.

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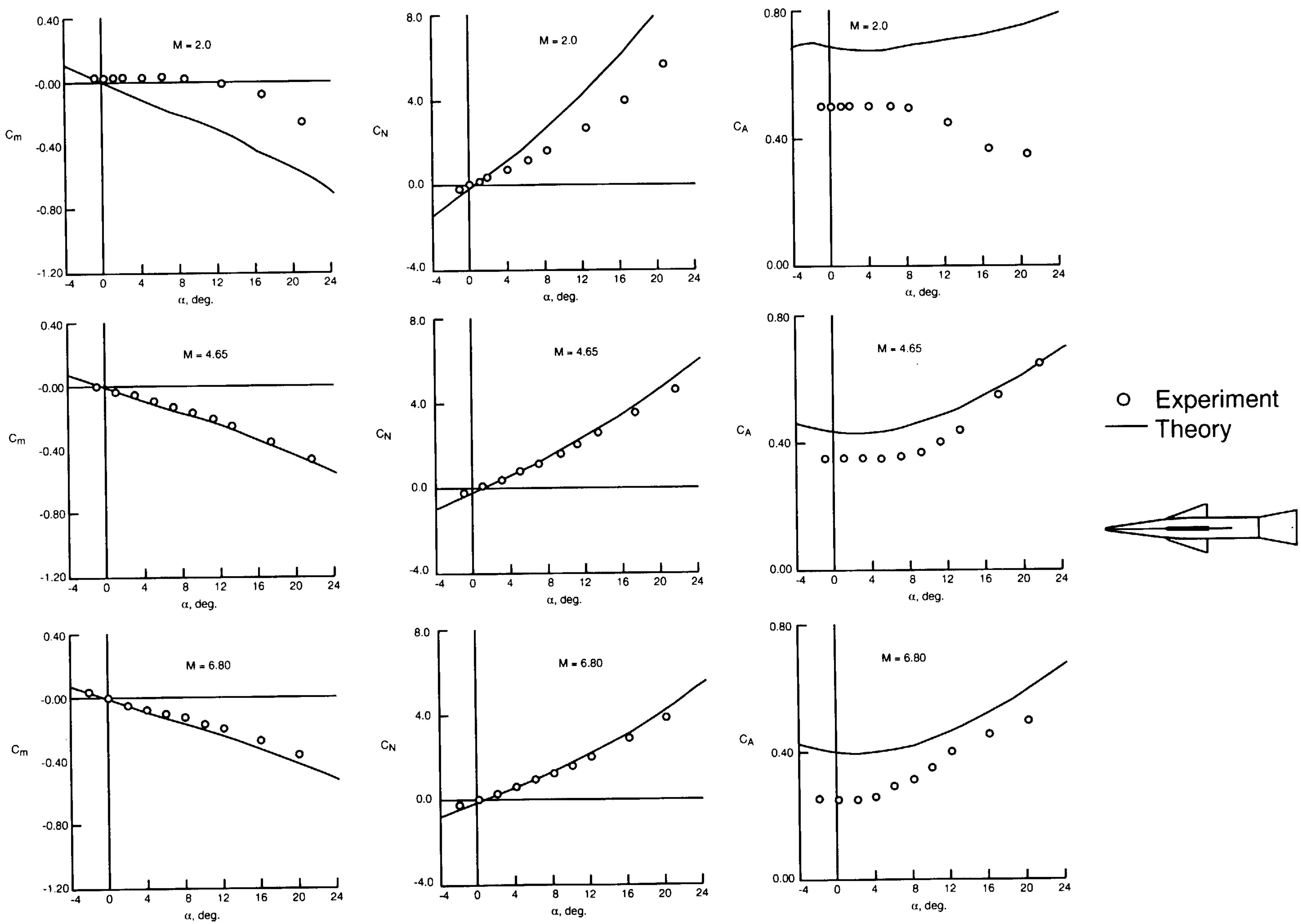

Figure 14 - Comparison of experiment and theory, flared-configuration with all-moving wing.

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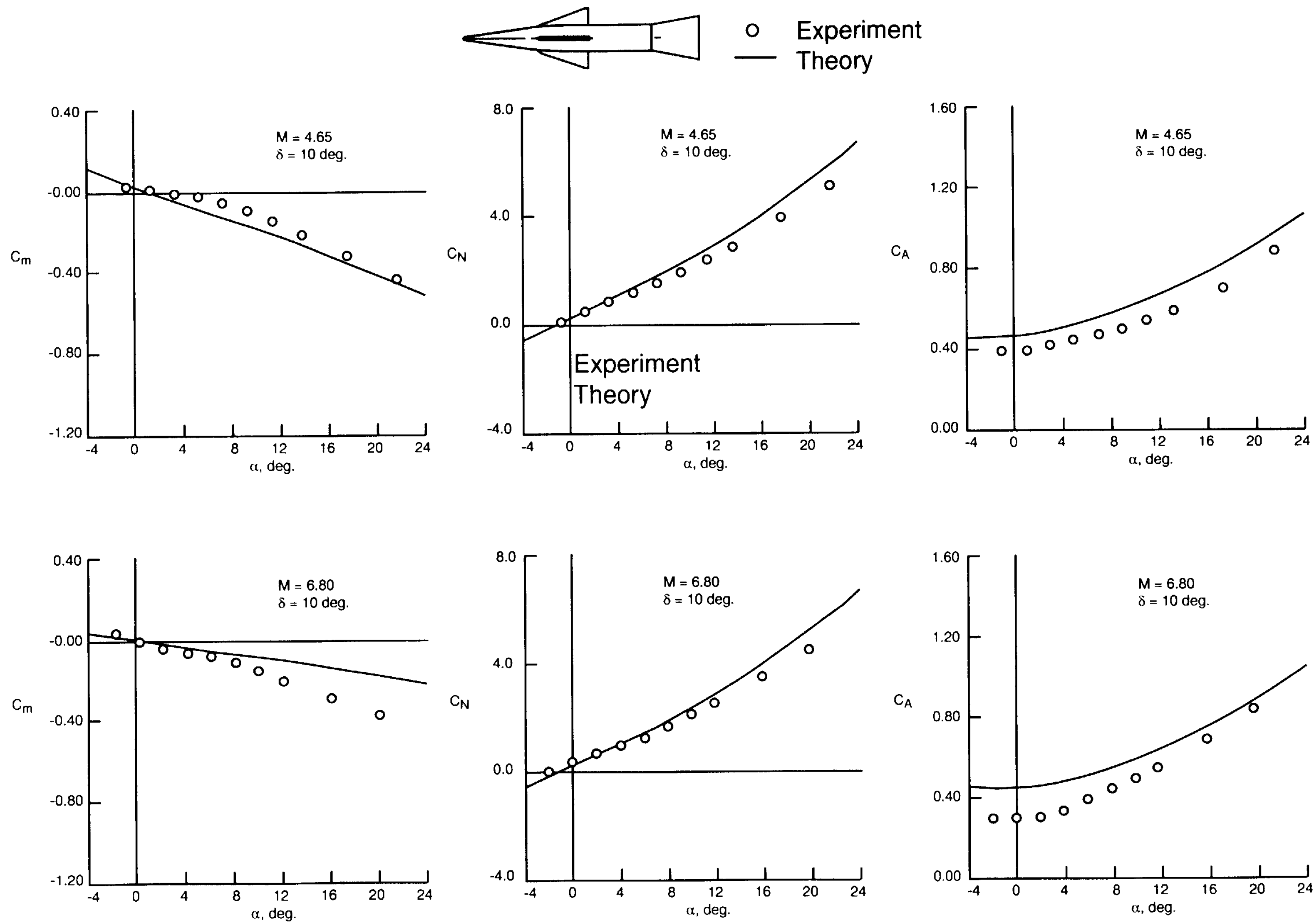

Figure 15 - Comparison of experiment and theory, flared-configuration with all-moving wing deflected 10°.

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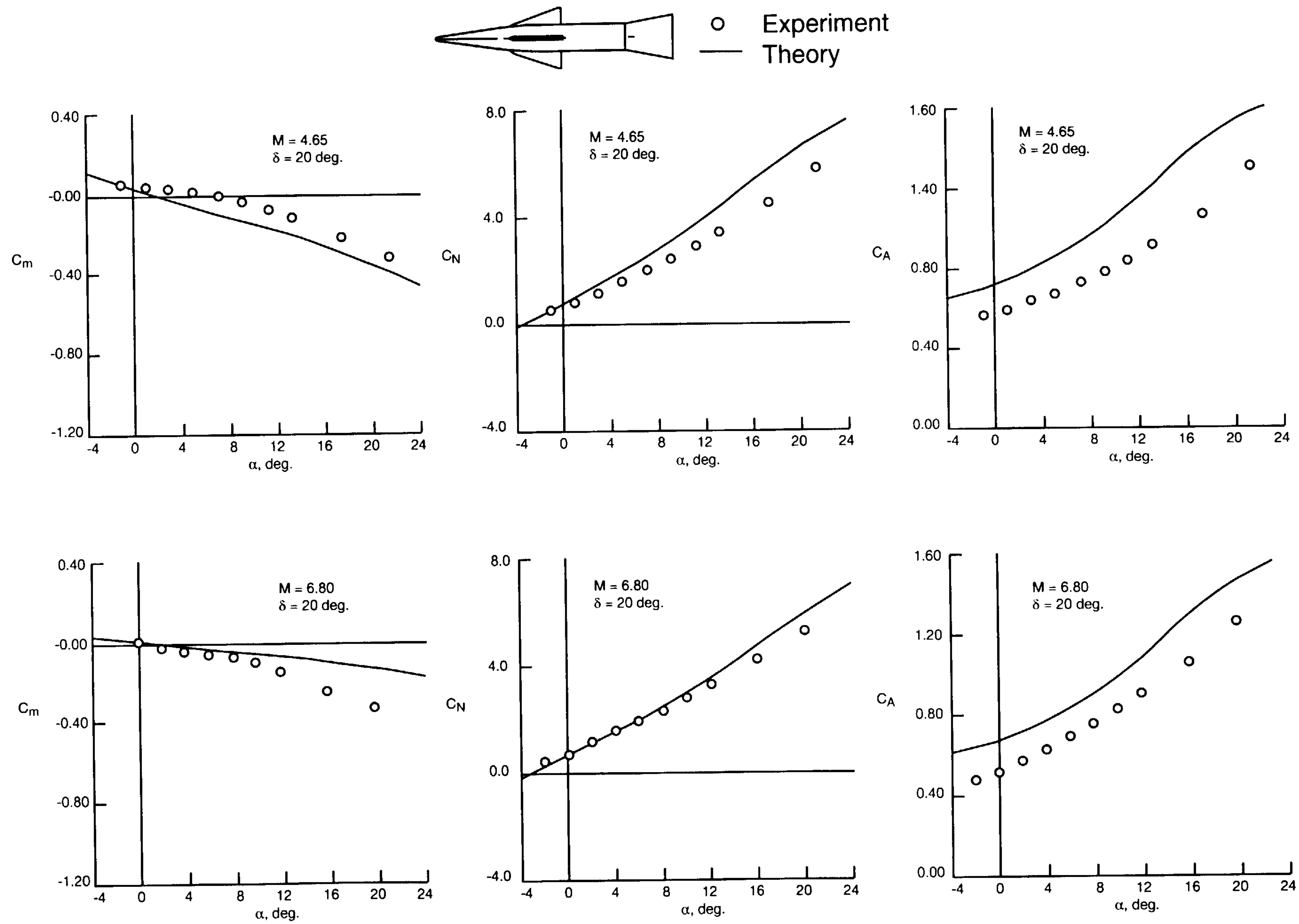

Figure 16 - Comparison of experiment and theory, flared-configuration with all-moving wing deflected 20°.

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13. ABSTRACT (*Maximum 200 words*)
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The results indicated that the addition of a flare, wings or tails to the basic body all provided static longitudinal stability with varying amounts of increased axial force. The control arrangements were effective in producing increments of normal-force and pitching-moment at the lower Mach numbers. At the highest Mach number, the flap control on the winged body was ineffective in producing normal-force or pitching-moment but the all-moving wing control on the flared body, while losing pitch effectiveness, still provided normal-force increments.

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